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Tank Side Cesium Removal IXC-150 Cask Detonation Report

Explosive Applications & Special Project Group

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Los Alamos NATIONAL LABORATORY

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1 Tank Side Cesium Experiment Overview (TSCR)

A set of experiments were conducted at Los Alamos National Laboratory's firing point 88 to determine the blast pressure and effects of a stoichiometric gas mixture of Hydrogen (H_2) and Nitrous Oxide (N_2O) on the IXC-150 Storage Pad Vent Stack assemblies. The Lab was asked to design, build, and test the vent stack assemblies using a reaction gas volume of 340 in^3 that mimics the Tank Side Cesium Removal (TSCR) Ion Exchange Column (IXC) assembly. The experimental system with vent stack assembly was designed with input from the Washington River Protection Services (WRPS) to ensure an accurate test setup.

The tests were conducted at LANL on the newly built filter/gas assembly at the end of April 2021 timeframe, using WRPS supplied vent stack assemblies and internal HEPA filters. The objective of these tests was to observe that the structural integrity of the vent stack assemblies was maintained and determine the resulting blast overpressures at a distance of 16 and 32 inches from the assembly.

All work was performed under the LANL Quality Assurance Program (SD330), using a graded application of ASME NQA-1-2008/NQA-1a-2009. To ensure that all client quality assurance (QA) expectations were addressed, evaluation of the end data needs was performed and the appropriate controls applied for this work.

2 Experimental Design

2.1 Reaction Volume and Gas Delivery Design

The experimental assembly was designed with a similar volume (340 in^3) to the TSCR IXC-150 Cask headspace and filter assembly, Figure 2:1. The vent stack assembly contains an internal HEPA filter that could be changed as needed to support testing (H-14-111266).

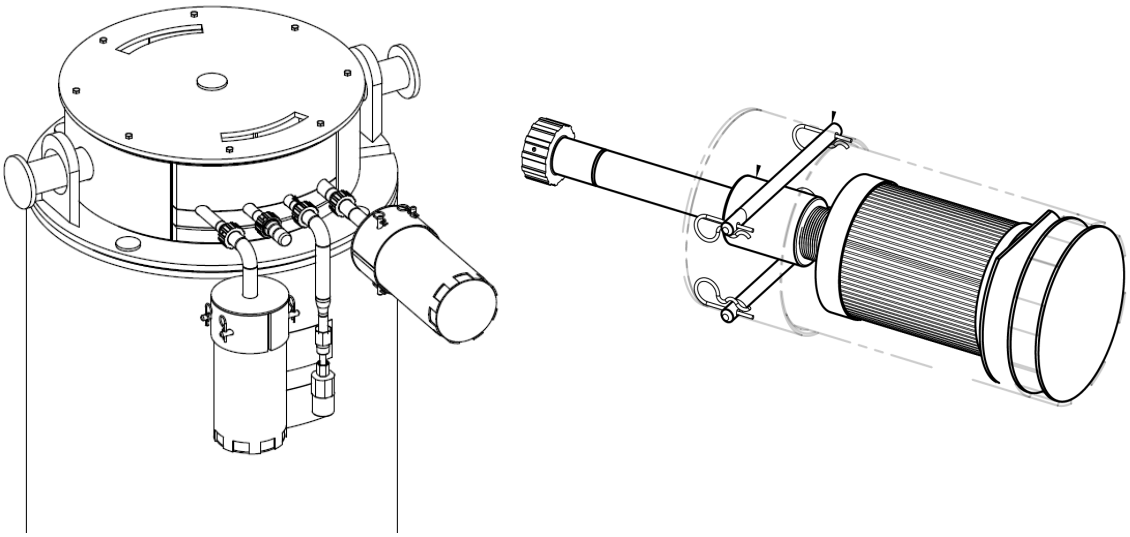

Figure 2:1 TSCR Cask Head Space and Hepa Filter Assembly

The piping geometry of the IXC head space was represented as a straight tube, allowing the gas mixture detonation to develop in a straight line. Determining detonation velocities from time of arrival measurements is more precisely defined and subject to less uncertainty in a straight tube, thus prompting the primary geometry of a straight tube. Additionally, this configuration represents lower resistance to the expansion of the detonating gas mixture providing a conservative evaluation of the vent stack assembly's structural integrity.

All of the test assembly reaction volume was designed using 2-3/4" Conflat (CF) Stainless Steel Vacuum Fittings and 1.5" Stainless Steel tubing. 2-3/4" CF Flanging was chosen due to its similarities to the bill of materials used in the IXC-150 design but allowed any for any potential test modifications later in testing, Figure 2:2.

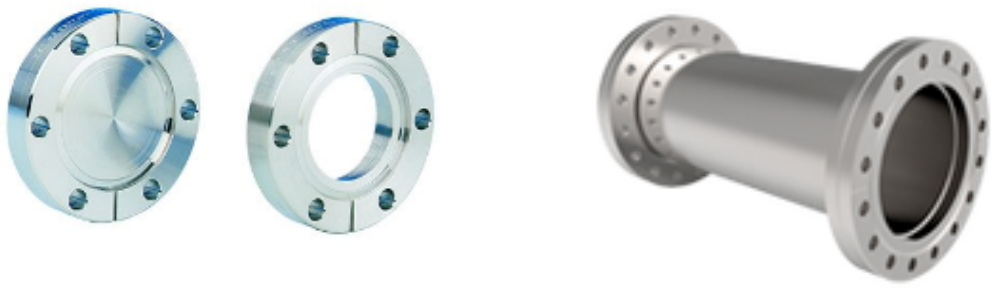

Figure 2:2 2-3/4" Conflat Vacuum Fittings and Tubing

Working with WRPS a 2-3/4" Conflat to Chem Joint Weld Adaptor fitting was designed and built to allow the mounting of the TSCR IXC-150 Vent Stack Assembly to the test reaction volume using a similar fitting to what was on the IXC-150, Figure, Figure 2:3.

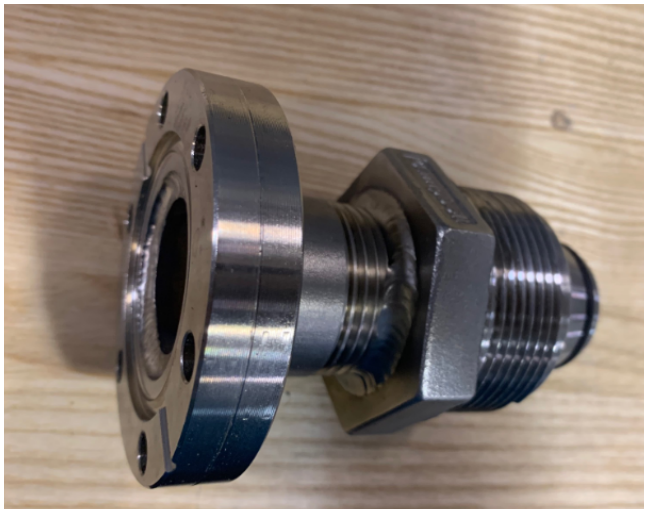

Figure 2:3 Chem Joint Weld Adaptor to 2-3/4" CF Fitting

As was noted earlier, the reaction volume was designed as a straight tube to make the gas detonation measurement more precise and with less uncertainty. Dynamic Pressure Gauges (PCB Piezoelectric PN: 113B22 High Frequency Pressure Sensor) were placed at 25”, 42”, 59” and 76” for PT-1 through PT-4, respectively, downstream from the initial detonation point allowing the denotation wave to develop in the stoichiometric mixed reaction gas. This would allow the timing measurement to be made for the detonation wave, that would be initiated by a Teledyn RISI RP-1 Exploding Bridge Wire Detonator head (i.e. all High Explosive was removed), at the beginning of the reaction volume, Figure 2:4.

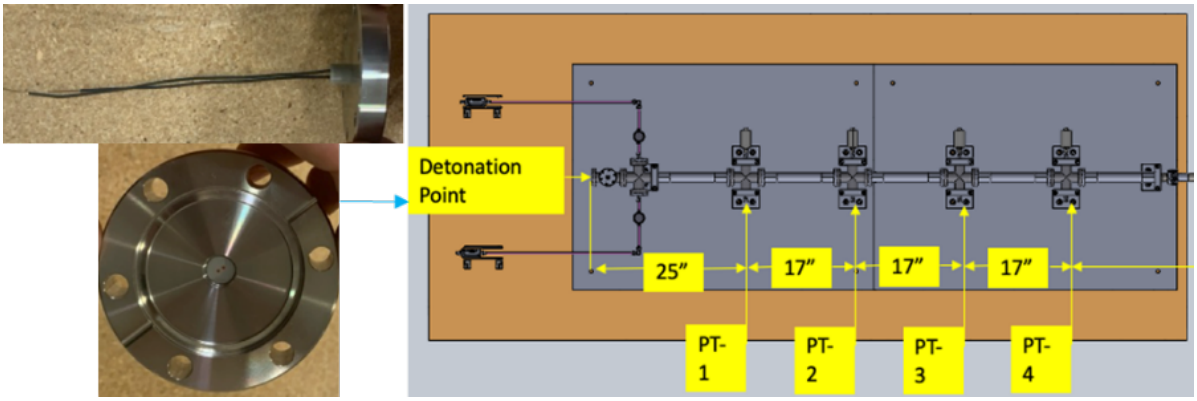

Figure 2:4 RISI RP-1 Header and Reaction Volume and Dynamic Pressure Gauges PT-1 through PT-4

Hydrogen (H_2) and Nitrous Oxide (N_20), would be co-flowed separately into the reaction volume, mixing in the reaction volume and creating the detonable gas mixture. The gas would be delivered from separate Type 1A Compressed Gas Cylinders bought from Matheson Tri-Gas. This was to be accomplished using two Brooks 5850E Mass Flow Controllers (MFC) through ¼” diameter, 0.035” wall thickness 316 Stainless Steel tubing. As the gas mixture was considered a detonable mixture, the gas delivery system and reaction volume needed to be controlled remotely from the safety of a bunker and only mixed when established safety procedures were followed, Figure 2:5.

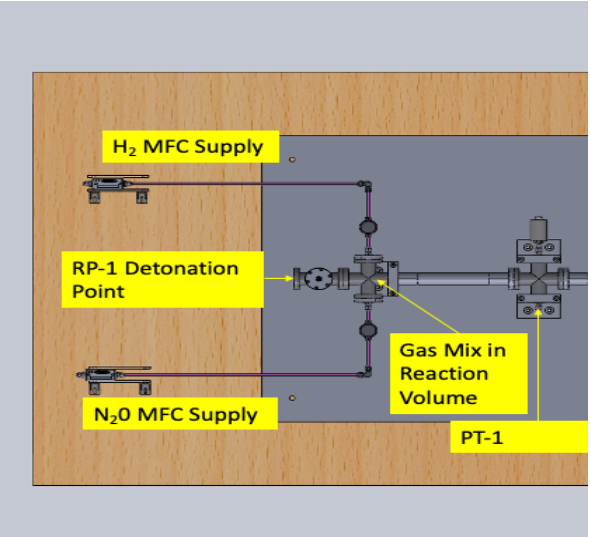

Figure 2:5 Remote Gas Delivery to Reaction Volume

Doing this would allow personnel to work around the reaction volume and gas delivery system without concern of detonation, and only produce a detonable gas mixture when the aforementioned safety procedures were followed and all personnel had been removed from the area and were in a safe location.

2.2 Detonation and Blast Pressure Diagnostics Design

The Detonation Diagnostic design was based previous LANL explosive diagnostic systems designed to measure detonation pressures. The design consisted of three main components, the dynamic pressure gauges in the reactive volume, the pencil gauges meant to measure the blast pressure once the detonation wave leaves the filter, and the signal conditioning/Oscilloscope which ultimately logs the test data. Figure 2.6 shows an Instrumentation Diagram of the diagnostics system.

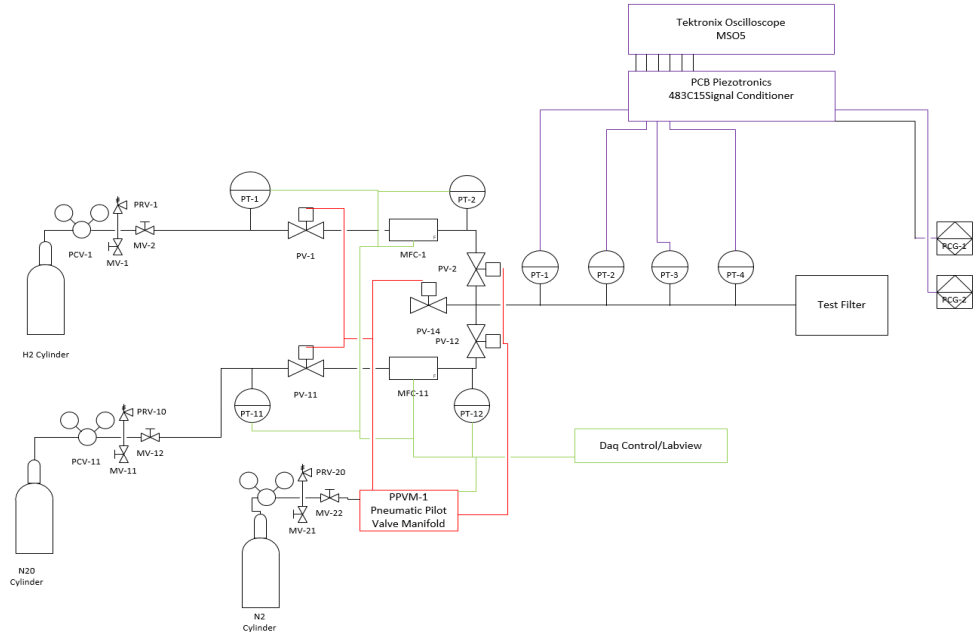

Figure 2:6 Instrumentation Diagram for the Detonation/Blast Pressure

The raw data collected by the Oscilloscope, consisting of two columns being time and measured voltage from the pressure and pencil gauges, would then be taken and processed using a graphing tool such as Origin or Microsoft Excel.

3 Experimental Setup

The TSCR IXC-150 Cask Filter Detonation Experiments were setup at Los Alamos National Laboratories Firing Point 88 located in Ancho Canyon. This site was chosen as it was a certified firing site for Explosive operations and had all the infrastructure and safety procedures needed to complete the tests. Figure 3.1, shows the complete TSCR IXC Vent Stack Assembly Detonation Experiment as it was tested

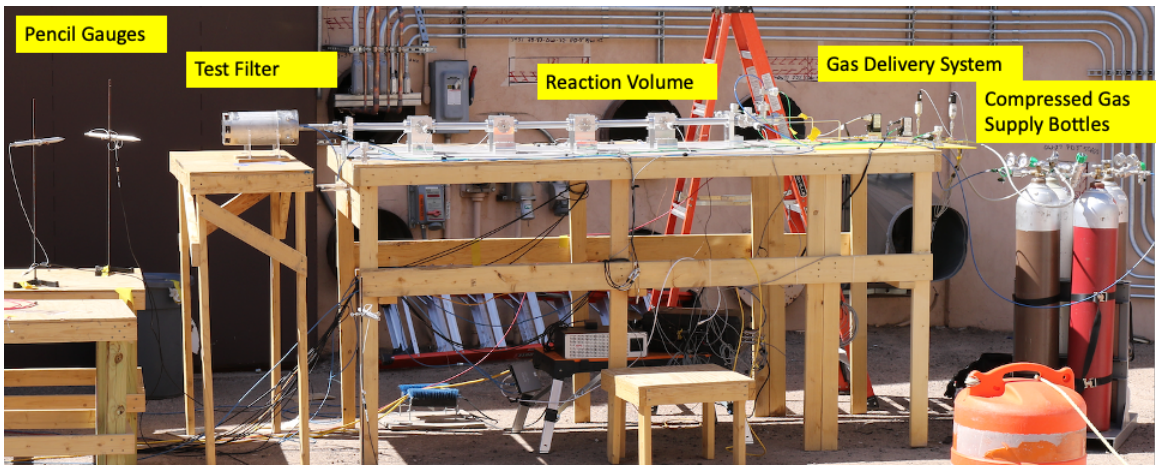

Figure 3:1 Actual Test Layout at Point 88

3.1 Chem Wipe Tests

Initial tests (shots 2b-5, “Chem Wipe Tests”) were conducted as a system check and to understand the impact of different gas flow rates used to fill the reaction chamber, and if this variation had any effect on the detonation characteristics. This test configuration utilized the main test assembly without the vent stack assembly installed. These test were conducted using a chemical wipe taped over the end of the Chem joint. This allowed for the system check testing to be performed without consuming HEPA filters as the number of filters available was limited. The configuration for this test effort is depicted in Figure 3:2.

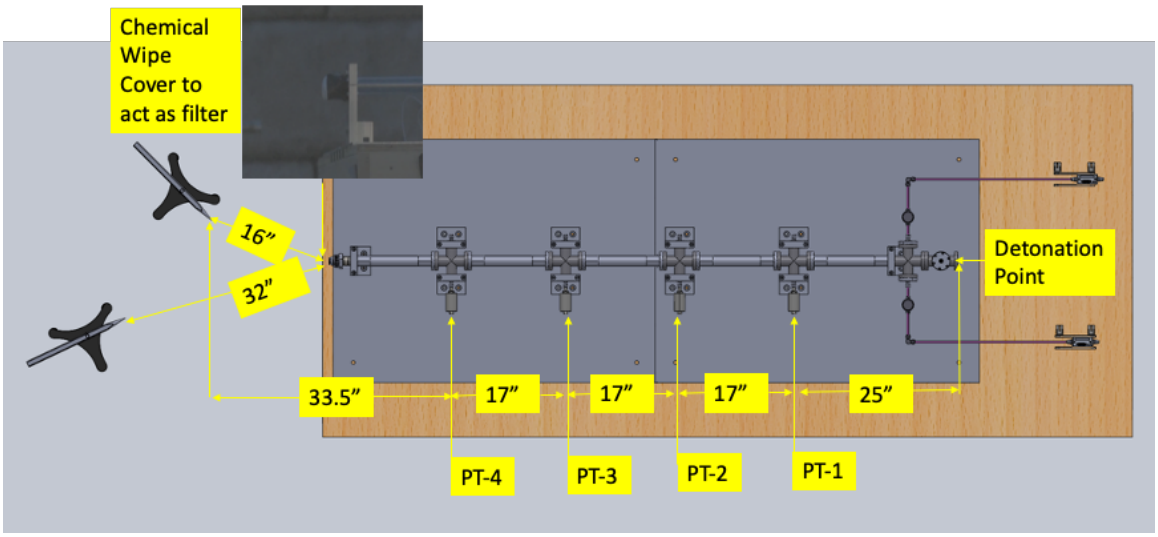

Figure 3:2 Hepa Filter End and Initial Test Layout

3.2 Nitrogen Purge Tests

A nitrogen purge (shots 6-10) was added to vent stack assembly to support removal of flammable gases in the annular space external to the HEPA filter and internal to the shroud of the assembly, performed after system charging. The horizontal filter assembly was used on these tests to determine the effects of nitrogen purge on the blast pressure. This configuration was utilized to help reduce the potential for pooling of detonable gas mixture in the annular space between the exterior of the HEPA filter and the interior of the shroud, figure 3:3 shows this test setup.

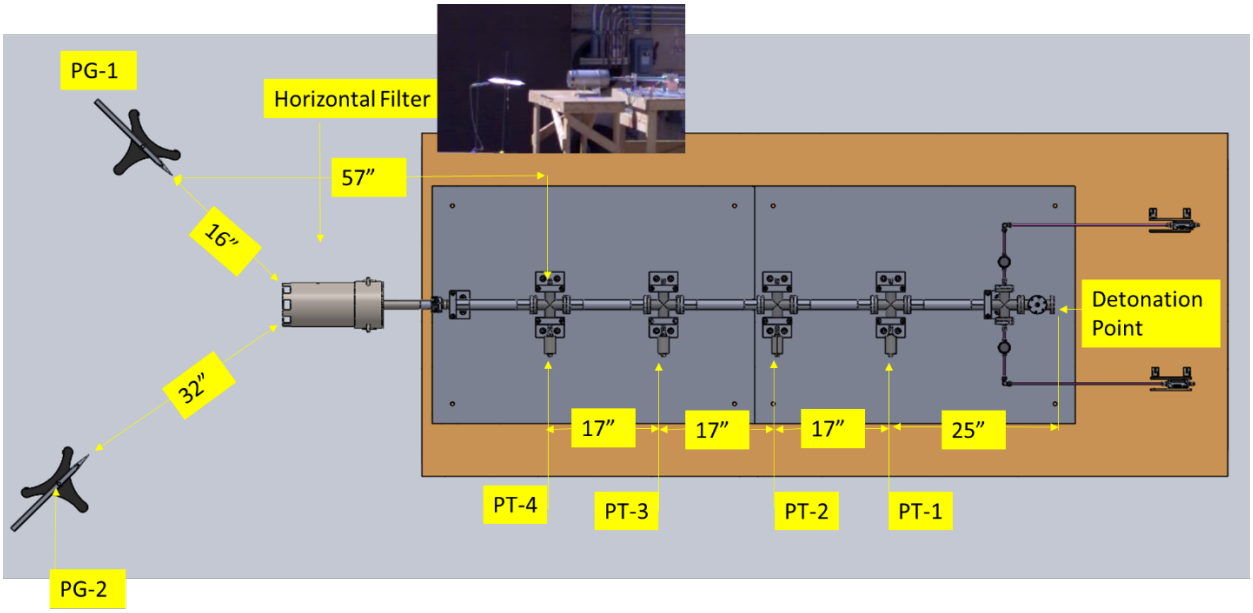

Figure 3:3 Nitrogen Purge Test Layout

3.3 Final Qualifying Tests

The final set of tests (shots 11 and 12) included both the horizontal and vertical filter assemblies, attached to the reaction volume figures 10 and 11. In this test configuration no nitrogen purge was utilized and test assembly was charged with a gas volume equivalent to the determined reaction volume.3:4 and Figures 3:5.

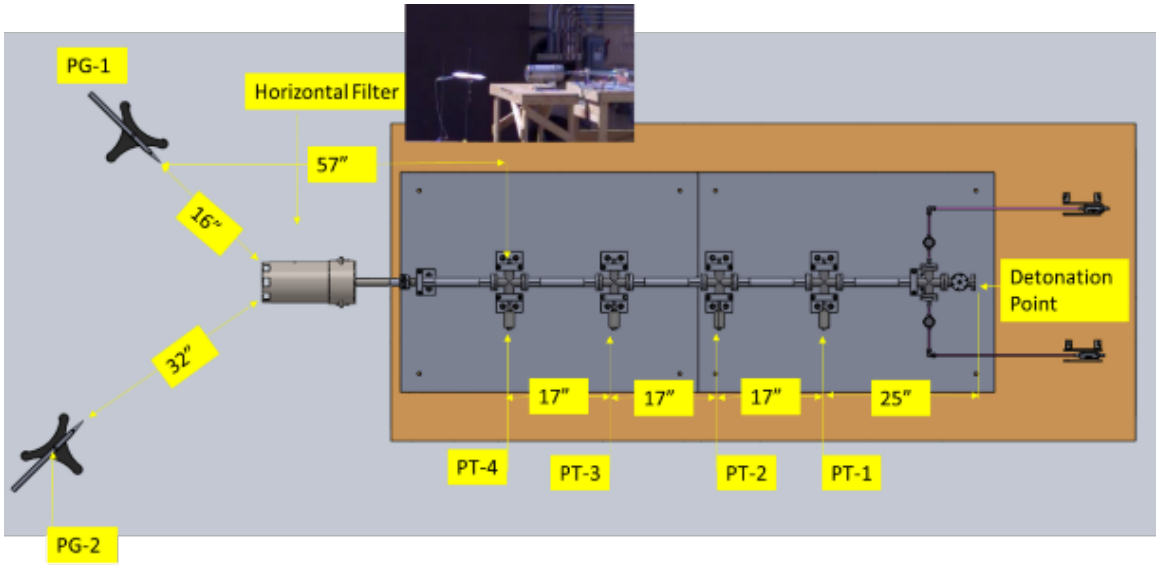

Figure 3:4 Horizontal Filter Test Layout

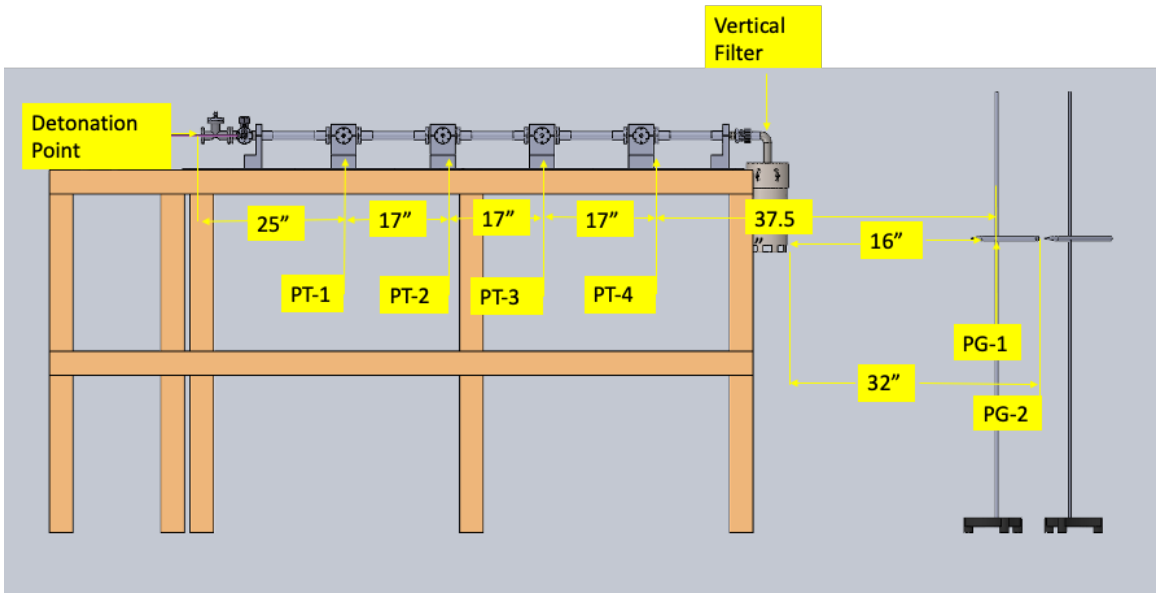

Figure 3:5 Vertical Filter Test Layout

4 Test Results

4.1 Chemical (Chem) Wipe Test Results

Shots 2b-5, the chem wipe tests, consisted of only the reaction volume (161 in^3) without the vent stack assembly. A chemical wipe was taped to the end of the chem joint to simulate an end filter. As noted previously this allowed for testing to be performed without consuming HEPA filters, as the number of filters available was limited. This also allowed the team to perform system checks including diagnostics and evaluate the impact of different flammable gas introduction flow rate and volumes. This became a parametric study in actual flow rates to be used for the final testing.

Table 4-1, is an overview of the parametric study completed with the chem wipe tests.

Table 4-1 Chem Wipe Test Pressure and Flow Rates

Shot	CombinedFlow (in^3/min)	Volume (in^3)	Minutes	Seconds	MFC Setpoint (in^3/min)	Manifold End	PT-1 (PSI)	PT-2 (PSI)	PT-3 (PSI)	PT-4 (PSI)	PG-1 (PSI)	PG-2 (PSI)
Shot 2B	152.55	160.48	1.05	63.06	76.28	Chem Wipe	606	557	500	697	1.31	0.97
Shot 3	305.10	160.48	0.53	31.53	152.55	Chem Wipe	1479	564	542	706	1.62	1.07
Shot 4	610.20	160.48	0.26	15.76	244.08	Chem Wipe	510	726	574	720	1.48	1.15
Shot 5	1220.40	1830.60	1.50	90.00	610.20	Chem Wipe	685	549	542	726	1.57	1.03
						Average	820	599	539.5	712.25	1.495	1.055
						Std Dev	385.49	73.52	26.28	11.41	0.12	0.07

The first question to answer was whether or not the mix gas detonated, this was accomplish by looking at the time of arrival of the detonation wave of PT’s-1 through PT-4, as seen in figure 4.1.

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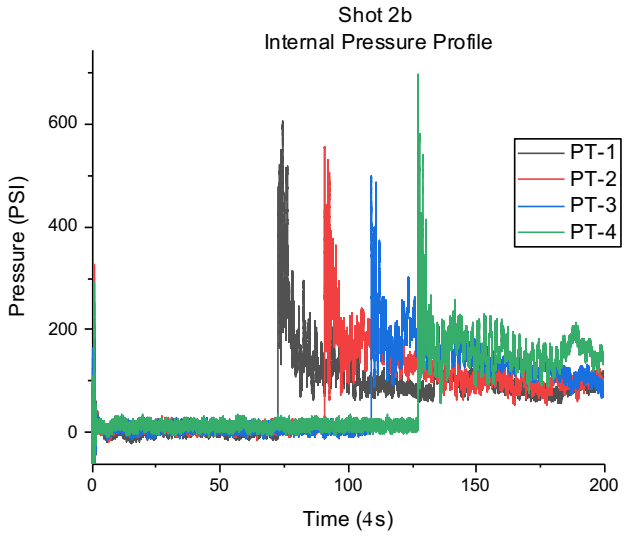

Figure 4:1 Detonation Wave Timing and Pressure Profile for Shot 2B.

Using PT-1 as time reference zero, the time difference between PT-1 and PT-2 is the time it took the wave to travel 17", thus giving a wave speed of 1.04E5 in/sec. This wave speed was faster than the calculated detonation velocity of the mixed gas at 7.87E4 in/sec *Appendix L: Stacks Cheeta Run Report*, thus detonation was achieved. Table 4-2, show that detonation occurred in all of the chem wipe tests.

Table 4-2 Detonation Wave Velocities.

Guages	Distances (in)	2b Det. Vel. (in/s)	3 Det. Vel. (in/s)	4 Det. Vel. (in/s)	5 Det. Vel. (in/s)
PT-1 to PT-2	17	1.04E+05	1.00E+05	8.95E+04	1.02E+05
PT-2 to PT-3	17	9.39E+04	8.50E+04	9.44E+04	8.95E+04
PT-3 to PT-4	17	9.44E+04	1.06E+05	1.00E+05	1.00E+05

The exhaust gasses from the detonation that came out of the reaction volume had the characteristic Mach diamonds, which give an indication that the static gasses inside the reaction volume before detonation were now supersonic when leaving the reaction volume, Figure 4:2.

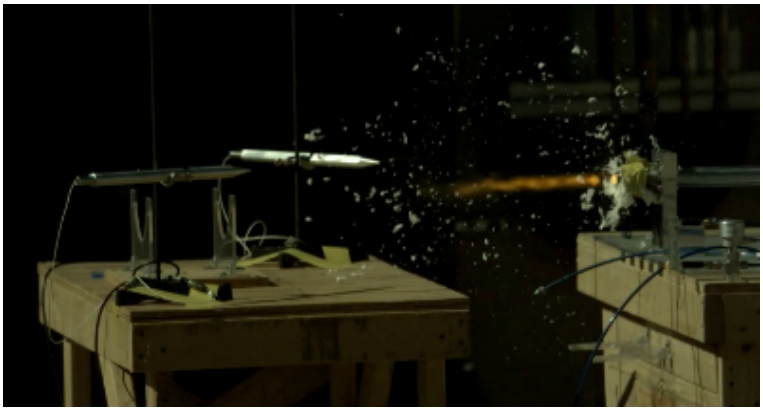

Figure 4:2 Mach Diamonds Observed in Tests 2b-5

Although the measured velocity described previously provides the evidence of detonation these Mach diamonds also provide indication that the reaction products are moving faster than the speed of sound. The pencil gauges, PG-1 and PG-2 set at a distance of 16" and 32" from the end of the reaction tube measured similar pressures in all of the chem wipe tests, indicating the neither the rate of gas introduction or volume added to the test assembly (within the range tested) impacted the outcome with respect to blast pressures observed outside the reaction volume, Table 4-3.

Table 4-3 Chem Wipe Test Pencil Gauge Pressures

Shot	Combined Flow (in^3/min)	Volume (in	Minutes	Seconds	MFC Setpoint (in^3/min)	PG-1 (PSI)	PG-2 (PSI)
Shot 2B	152.55	160.48	1.05	63.06	76.28	1.31	0.97
Shot 3	305.10	160.48	0.53	31.53	152.55	1.62	1.07
Shot 4	610.20	160.48	0.26	15.76	244.08	1.48	1.15
Shot 5	1220.40	1830.60	1.50	90.00	610.20	1.57	1.03

4.2 Nitrogen Purge Test Results

Another question to answer was whether or not the HEPA filter shroud would trap a detonable gas mixture between the exterior of the HEPA filter and interior of the shroud. An inert gas (nitrogen) purge was added to the space between the filter and the shroud, which was meant to purge any detonable gas mixture from this space but not interfere with the detonable gas in the filter assembly and the

reaction volume. Shots 6 used a complete (new) HEPA filter assembly with the shroud attached and a 1.5 minute N2 purge after a 1.5 minute charging of the test assembly with H_2 and N_20 into the reaction volume and filter assembly at a combined flow rate of 1220 in^3/min (20 LPM). Shots 7-9 reused the HEPA filter that was utilized in shot 6, as there was a limited number of filters for testing, table 4 shows that the Nitrogen Purge definitely effected the blast pressure.

Table 4-4 Nitrogen Purge Tests Pressure and Flow Rates (Shot 6-10)

	CombinedFlow (in^3/min)	Volume (in^3)	Minutes	Seconds	MFC Setpoint (in^3/min)		PT-1 (PSI)	PT-2 (PSI)	PT-3 (PSI)	PT-4 (PSI)	PG-1 (PSI)	PG-2 (PSI)
Shot 6	1220.40	1830.60	1.50	90.00	610.20	Horiz. New Filter, N2 Post Purge 1.5 min	531	567	529	691	0.10	0.09
Shot 7	1220.40	1830.60	1.50	90.00	610.20	Used Shot 6, No N2	727	541	537	711	0.41	0.41
Shot 8	20.00	30.00	1.50	90.00	610.20	Used Shot 6, No N2	1435	600	493	689	0.26	0.16
Shot 9	20.00	30.00	1.50	90.00	610.20	Used Shot 6, N2 Post Purge 1.5 Min	657	532	507	700	No Registered Signal	No Registered Signal
Shot 10	2.50	2.63	1.06	63.37	76.28	Horiz. New Filter, No N2	616	559	558	682	No Registered Signal	No Registered Signal
						Average	837.50	560.00	516.50	697.75	0.26	0.22
						Std Dev	352.04	26.43	17.46	8.70	0.13	0.14

Shot 7 registered a higher pressure due to the fact that the cotter pins connecting the shroud to the assembly were not reinstalled after inspection following shot 6. This configuration resulted in the shroud being ejected off the remainder of the vent stack assembly, therefore resulting in a higher blast pressure than expected with the shroud affixed to the assembly, Figure 4:3. After this event the shroud was inspected for damage and found to be in satisfactory condition before continuing with the test activities.

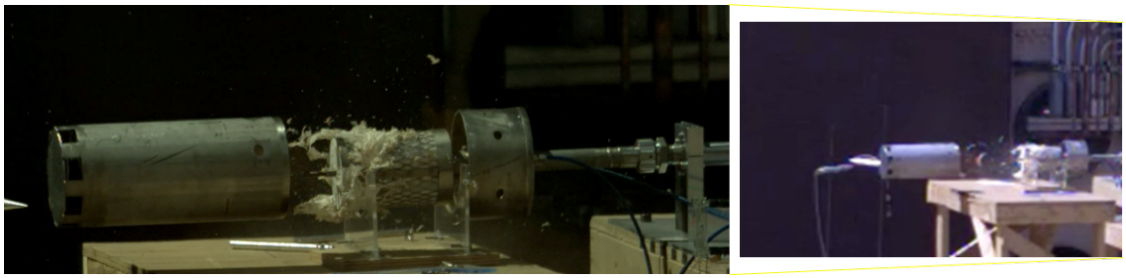

Figure 4:3 Shot 7 Shroud

Again detonation wave speed was calculated for each test and again it was determined that all tests' mixed gas detonated, Table 4-5.

Table 4-5 Detonation Wave Velocities

Guages	Distances (in)	6 Det. Vel. (in/s)	7 Det. Vel. (in/s)	8 Det. Vel. (in/s)	9 Det. Vel. (in/s)	10 Det. Vel. (in/s)
PT-1 to PT-2	17	9.35E+04	9.64E+04	1.00E+05	1.01E+05	1.03E+05
PT-2 to PT-3	17	9.91E+04	1.00E+05	1.06E+05	9.34E+04	1.04E+05
PT-3 to PT-4	17	8.95E+04	9.44E+04	9.44E+04	8.95E+04	8.10E+04

Looking at the Pencil Gauges it was determined that the Nitrogen Purge does effect the blast pressures by reducing them by almost an order of magnitude. It was determined that the nitrogen purge not only purges the mixed gas from the volume between the shroud and the HEPA filter, but can also aid in diffusion of the gases behind the HEPA filter in the test assembly. This resulted in a configuration that was different than the existing analysis efforts and represented a less than bounding test. It was decided for the final qualifying tests the nitrogen purge would not be used.

4.3 Final Qualifying Test Results

Using the information gained from the Chem Wipe and Nitrogen Purge Tests, the Final Qualifying test parameters were developed. The H_2 and N_20 were co-flown into the reaction volume at a flow rate of 152.6 in^3/min, for 1 minute 7 seconds, filling the entire reaction volume and HEPA filter portion of the vent stack assembly. Within 5 seconds of stopping the flow of the gasses into the reaction volume and HEPA filter, the gas mixture was detonated. Table 4-6 shows the detonation wave velocities for each test first the horizontal filter assembly and then the vertical filter assembly.

Table 4-6 Final Qualifying Test Results: Detonation Wave Velocities

Guages	Distances (in)	11 Det. Vel. (in/s)	12 Det. Vel. (in/s)
PT-1 to PT-2	17	1.00E+05	1.04E+05
PT-2 to PT-3	17	9.00E+04	9.15E+04
PT-3 to PT-4	17	9.44E+04	8.95E+04

Detonation was achieved as the det velocities in the vent stack assembly were faster than the calculated detonation velocity of the mixed gas at 7.87E4 in/sec.

For shot 11, horizontal filter assembly, the pencil gauges registered pressures of 0.26 and 0.13 PSI at 16 and 32" respectively. For shot 12, vertical filter assembly the pencil gauges registered pressures of 0.19 and 0.10 PSI at 16 and 32" respectively. In all tests the structural integrity of the vent stack assembly was maintained. No visible damage from the blast pressure was observed upon inspection of the structural components of each assembly. The structural integrity of the frame for the radial HEPA filter was also maintained; however, the filter media within the frame sustained damage, as shown in in Figure 4:5. Most filter media "confetti" that resulted from the blast was retained within the shroud, while small amounts could be observed outside the shroud assembly following the blast

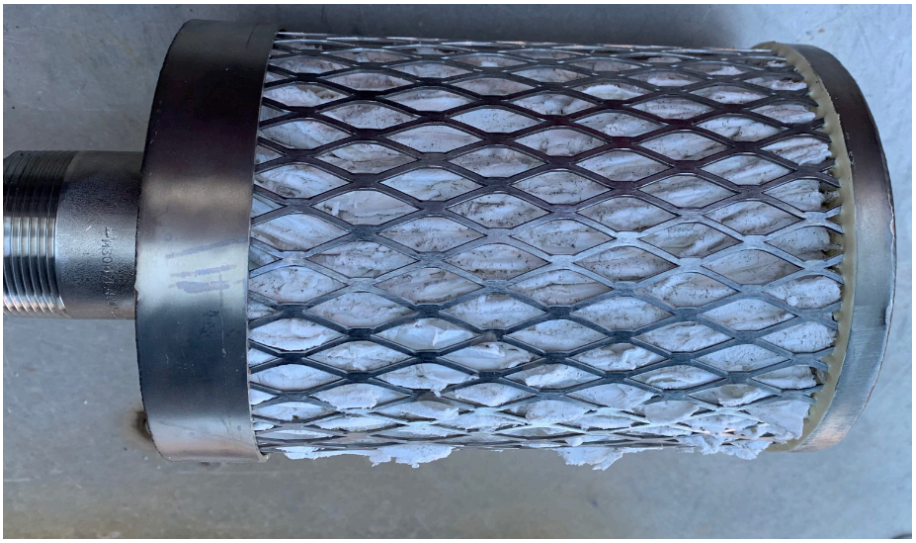

Figure 4:4 Blast Pressure Damage to Hepa Filter

4.4 Test Results Summary and Conclusion

Blast Pressures were measured at distances of 16" and 32" from the end of the TSCR IXC-150 HEPA Filter assembly for both the horizontal and vertical filter geometries. Blast pressures were measured at 0.26 and 0.13 PSI at 16" and 32" respectively for the horizontal test and 0.19 and 0.10 PSI at 16 and 32" respectively for the vertical filter assembly. The structural integrity of the vent stack assembly was maintained. The structural integrity of the frame for the radial HEPA filter was also maintained withstanding the blast pressure without any damage. The filter media within the HEPA filter frame did not withstand the detonation of the stoichiometric gas mixture of H2/N2O, as anticipated.

It should be noted that the stainless steel shroud for the horizontal vent stack assembly can become a projectile during detonation if the shroud pins are not in place. Additionally, each test conducted did result in a detonation of the gas mixture regardless of flow rates into the reaction volume, within the range tested.

5 TSCR Quality Assurance (QA)

The Tank Side Cesium Removal System (TSCR)-Vent Filtration Tests comply with LANL's Quality Assurance Program through Explosives Science and Shock Physics Division Quality Assurance Plan on a graded approach. The TSCR - Vent Filtration testing is providing data collection as further confirmation to calculations performed for analysis of the ignition of a stoichiometric mixture of hydrogen (H_2) and nitrous oxide (N_2O) within the applicable IX column piping and IXC-150 Storage Pad Vent Stack assembly. The results of the testing is for confirmation of calculations and analysis performed by Washington River Protection Solutions (WRPS) supporting development of the TSCR Documented Safety Analysis (DSA). Test plan Quality Levels are based on the hazard category of the TSCR Facility in conjunction with a graded approach for R&D. The data collection process is the most critical component of the test report, and testing equipment (oscilloscopes, pen gauges) are requested by PNNL to adhere to specific NQA-1 requirements.

5.1 Quality Assurance Scope

The scope of Quality Assurance NQA-1 Requirements provided by WRPS are specifically applicable to the items in Table 5-1:

Table 5-1 NQA-1 Applicable Items

Equipment/Item	Version/ Information	Quality Calibration Certificate Number
Tektronix 5 Series MSO Low Profile MSO58LP Oscilloscope	1.26.5.7750 –rel- (Date 2020-03-19 Time 16:24:57)	2016858-2-MSO58LP-B010925-1
Tektronix 5 Series MSO58 Oscilloscope	1.26.5.7750 –rel- (Date 2020-03-19 Time 16:24:57)	2016858-MSO58-C012629-1
PCB Pen Pressure Gauges	PCB Piezoelectric PN:113B22 High Frequency Pressure Sensor	*See LANL Calibraion Certification in Appendix*

Activities and equipment not related to the aforementioned Table 5-1 adhere to R&D associated Quality Assurance procedures. The integrity of the data collected is the critical component of all test run, and although the activities conducted to obtain the test information follow internal LANL processes, the equipment and subsequent data collection adhered to additional rigor to meet or exceed the Quality Assurance standards prescribed through the Appendix A: TSCR-Vent Filtration Quality Assurance Requirements (TSCR- QAR-03-18-2020)

5.2 Management Level Determination & Software Determination

Management level determinations are made based on the information provided by the Design Authority Representative from Washington River Protection Solutions. WRPS and PNNL request LANL to handle testing equipment as Safety Significant for a HC 2 Nuclear Facility. Per the Conduct of Engineering (CoE) Management Level Determination, equipment designated as Safety Significant per a Facility's Safety Basis shall be managed to ML-2. Therefore, the equipment shall be designated and managed to ML-2 for this R&D testing.

5.3 Instructions Procedures and Drawings

All activities affecting quality are performed in accordance to the Design of LANL's Subject Matter Expert (SME) and communicated with the project sponsors. Internal Responsible Line Management and sponsor review the Design and approach for technical accuracy. It is agreed, by all parties involved in the TSCR Project, that procedures and drawings provided meet qualitative acceptance criteria for the project. All TSCR experiment design information and drawings of approved set up are included in this report.

5.4 Procurement of Items & Services for NQA-1 Applicable Items

Procurement of items and services obtained for the testing equipment on Table 5-1 NQA-1 Applicable Items followed the internal LANL process, compliant with NQA-1 requirement 4 Procurement Document control section 100 as required and Requirement 7 Control of Purchased Items and Services. The Institutional Evaluated Suppliers List (IESL) is used for the calibration and procured services, needed to comply with the requested QA requirements. All suppliers listed on the IESL have demonstrated compliance to LANL's quality program, which includes Management Level 2 procurements. Procurement records are maintained in the institutional procurement system of record.

5.5 Handling, Storage and Shipping

Part of the Quality Assurance process at LANL includes the Handling, Storage and Shipping requirements of Management Level 2 procurements. Required processes are followed for the identification of quality clauses related to the procured items and in compliance with NQA-1. For the Items identified on Table 5-1, specific salient features are document and inspected upon receipt of the procured items. Documentation is maintained in the system of record and in accordance with internal LANL procedure.

5.6 Metrology and Calibration

The Metrology Program and Calibration Laboratory provide services for measuring inspection and test equipment used in support of NQA-1 activities. The Standards & Calibration (S&CL) maintain competence of testing and calibration through ISO/IEC 17025-2017 accreditation through the National Voluntary Laboratory Accreditation Program (NVLAP 200936-0). This accreditation is cross-walked to NQA-1 2008/1a-2009 quality requirements and is an accepted Quality Assurance Program.

5.6.1 *Test Control*

The NQA-1 Applicable Items listed on Table 5-1 require an evaluation by the S&CL and subsequently obtain LANL calibration certification numbers. In order to meet or exceed the NQA-1 requirements, a thorough testing plan was discussed and approved by the project team. All items procured were tested and certified by the manufacturer. LANL ensured PCB Piezotronics is qualified to preform the certification and the critical criteria tested. American Association for Laboratory Accreditation Certification for PCB Piezotronics was obtain and is listed as Attachment B: PCB A2L2 Certification and Scope. Upon receipt of NQA-1 Applicable Items, LANL S&CL conducts testing to validate the manufacturer certification of the items, and to ensure shipping and handeling of the items did not impact equipments certified measurement capabilities before use. Once the calibration review is complete items are released to the project team for use. Administrative process for the addition of items to the S&CL list of managed equipment is completed and the final calibration number is assigned. Due to the expedited request for report of experimentation, use of some items may have been sooner than the completion of instrumentation paperwork. This is not quality effecting, and remains NQA-1 compliant. However, in an effort to remain transparent and prevent confusion from final certification dates and use dates, clarification is warrented.

Manufacturer certification is also provided for review of item B01925 as *Appendix C: Oscilliscope Manufacturer Certification*. Manufacturer testing of the oscilloscope included 1542 tests (e.g. DC Gain, DC Balance, Random noise, etc.). All tested characteristics and parameters pass and a calibration data report is provided by the manufacturer. LANL certification documentation from the S&CL is provided for Oscilloscope : Serial Number BO1925 as *Appendix D:Oscilloscope LANL Calibration Certificate # 141020* as assurance of quality complianc.e The LANL Calibration Certificate provides traceability to the activities completed by S&CL and to supporting test documentation for assurance of NQA-1 compliance. In order to demonstrate the traceabilty of testing control requirements to identified NQA-1 Applicable items, certificates from both the manufacturer and LANL S&CL are provided as Appendix C & *Appendix D*. All LANL generated certifications and associated file numbers are provided in *Table 5-2 TSCR Stack Detonation Instrumentation: Calibration Certification*. LANL Certificates for all NQA-1 Applicable items are included in the appendix as Appendix C through Appendix K.

Table 5-2 TSCR Stack Detonation Instrumentation: Calibration Certification

Cable	Gage Name	LANL Calibration File #	LANL Certificate Number	Serial Number	Exp. Date
1	PT-21	119293	164362	LW46628	12/30/21
2	PT-22	119294	164364	LW49205	01/08/22
3	PT-23	119296	164367	LW47057	12/29/21
4	PT-24	119295	164366	LW47056	12/30/21
5	PG-1	119292	164369	15343	01/20/22
6	PG-2	119291	164368	15342	01/20/21
SG	SG	119290	164386	555	12/22/21
OSCOPE	OSCOPE	117349	141020	B01925	07/16/21

5.6.2 *Control of Measuring and Test Equipment*

LANL maintains a comprehensive Control of Measuring and Test Equiptment Program through Meterology and Calibration. For the Control of Measuring and Test Equipment, relevant processes necessary to ensure the equipment has been managed according to NQA-1 quality standards are previously described. However, LANL would like to provide additional assurance to our internal processes by outlining the standards implemented. LANL uses the *ANSI/ISO/International Electrotechnical Commission (IEC):17025, General Requirements for the Competence of Testing and Calibration Laboratories,* as well as, *ANSI/NCSL Z540-1-1994, Calibration Laboratories and Measuring and Test Equipment—General Requirements.* These standards are implemented to control the Calibration System, which assures the measuring and test equipment accuracy. LANL is a proponent of excellence and quality programs, through established quality controls, ensuring compliance to outlined requirements.

5.7 Inspection

Inspection of NQA-1 Applicable Items are verified for conformance to outlined requirements at receipt inspection, and again through the LANL C&SL. Internal LANL Procedures assure NQA-1 quality standards are met for activities and tests that may affect the safe, secure, effective, efficient, and reliable data obtained for the TSCR Test.

5.8 Document Control

Document Control Procedures at LANL are intrinsic to internal process. Each activity required for the procurement or management of the NQA-1 identified items listed in Table 5-1 are invoked, and comply with the document control requirements located in NQA-1 Requirement 6, all sections. In an effort to distribute, maintain, and classify the report findings, review and approval for Scientific and Technical Information is performed and a unique

identifying number is provided. Any subsequent changes or additional work would require a new report and subsequent review and approval, thus changing the unique identifying document number.

5.8.1 *Quality Assurance Records*

Quality Assurance Records associated with the TSCR Test are maintanined in their designated system of record, and are maintained in accordance with the established requirements.

Acronyms and Abbreviations

Acronym	Definition
A2L2	Association for Laboratory Accreditation Certification
ALARA	as low as reasonably achievable
CF	Conflat
DSA	Documented Safety Analysis
IESL	Institutional Evaluated Suppliers List
IQPA	Institutional Quality Performance Assurance
LANL	Los Alamos National Laboratory
MCF	Mass Flow Controllers
ML	Management Level
NNSA	National Nuclear Security Administration
NQA-1	Nuclear Quality Assurance -1
PSI	Pound Per Square Inch
PT	Pressure Test
PNNL	Pacific Northwest National Laboratory

PCB	PicoCoulomB
R&D	Research and Development
RP	
S&CL	Standards and Calibration
SQA	Software Quality Assurance
TA	Technical Area
TSCR	Tank Side Cesium Removal System
WRPS	Washington River Protection Services

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Acknowledgements

The project team leadership would like to acknowledge the following contributors for their work:

Contributor	Area of Contribution	Affiliation
Blake Nolan	Technical SME	Los Alamos National Laboratory
Tim Foley	Responsible Line Manager	Los Alamos National Laboratory
Vikram Ahluwalia	Video Cameras	Los Alamos National Laboratory
Eva Baca	Firing Site Lead	Los Alamos National Laboratory
Dennis Herrerra	Firing Site Lead	Los Alamos National Laboratory
Rebecca Oertel	Firing Site Support	Los Alamos National Laboratory
Andrew Barnes	Systems Engineer	Los Alamos National Laboratory
Zak Kennison	Systems Engineer	Los Alamos National Laboratory
Sean Madden	Systems Engineer	Los Alamos National Laboratory
Veronica Camarillo-Morris	IQPA: IQ/SQA	Los Alamos National Laboratory
Mat Landon	Project Sponsor	Washington River Protection Services (WRPS)
Philip Schonewill	Technical Collaborator	Pacific Northwest National Laboratory
Paul Dixon	Project Stakeholder	Los Alamos National Laboratory
Paul Dickson	Project Stakeholder	Los Alamos National Laboratory
Ernest Albin	Project Oversight	National Nuclear Security Administration : (Los Alamos Sight Office)

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Appendix A: TSCR- Vent Filtration Quality Assurance Requirements

Washington River Protection Solutions
QUALITY ASSURANCE REQUIREMENTS

Revision No.: 000

Requisition No.:	Safety Classification: ☐ SC ☒ SS ☐ GS	Quality Level: ☐ QL-1 ☒ QL-2 ☐ QL-3	
Quality Assurance Engineer*: John Martin	Date: 3-17-2020	Design Authority/Engineer*: Matt Landon	Date: 3/17/2020
Project Number: TD101	Title: TSCR Vent-Filter Testing - PNNL/LANL		

*QAE/DA/Engineer name if attached in Electronic Procurement System, otherwise, print, signature, and date.

Evaluation Criteria

The ASME NQA-1 requirements checked below apply to this procurement. Clarifications are provided when the extent of coverage varies or when exceptions are taken. If no clarification is provided, the requirement applies as written.

Section A

ASME Version	NQA-1	NQA-1a	NQA-1b
Edition/Year	☒ 2008	☒ 2009	☐ 2011

NQA-1 Part I

(All) OR (Specify)

☐ **1. Organization**
- ☒ 100 Basic
- ☐ 200 Structure and Responsibility
- ☐ 300 Interface Control

☐ **2. Quality Assurance Program**
- ☒ 100 Basic
- ☐ 200 Indoctrination and Training
- ☐ 300 Qualification Requirements
- ☐ 400 Records of Qualification
- ☐ 500 Records

☐ **3. Design Control**
- ☐ 100 Basic
- ☐ 200 Design Input
- ☐ 300 Design Process
- ☐ 400 Design Analyses
- ☐ 500 Design Verification
- ☐ 600 Change Control
- ☐ 700 Interface Control
- ☐ 800 Software Design Control
- ☐ 900 Documentation and Records

☐ **4. Procurement Document Control**
- ☒ 100 Basic
- ☐ 200 Content of the Procurement Documents
- ☐ 300 Procurement Document Review
- ☐ 400 Procurement Document Changes

☐ **5. Instruction Procedures and Drawings**
- ☒ 100 Basic

☒ **6. Document Control**
- ☒ 100 Basic
- ☒ 200 Document Control
- ☒ 300 Document Changes

☐ **7. Control of Purchased Items and Services**
- ☒ 100 Basic
- ☒ 200 Supplier Evaluation Selection
- ☐ 300 Bid Evaluation
- ☐ 400 Control of Supplier Generated Documents
- ☐ 500 Acceptance of Item or Service
- ☐ 600 Control of Supplier Nonconformances
- ☐ 700 Commercial Grade Items and Services
- ☐ 800 Records

☐ **8. Identification and Control of Items**
- ☒ 100 Basic
- ☐ 200 Identification Methods
- ☐ 300 Specific Requirements

☐ **9. Control of Special Processes**
- ☐ 100 Basic
- ☐ 200 Process Control
- ☐ 300 Responsibility
- ☐ 400 Records

☐ **10. Inspection**
- ☒ 100 Basic
- ☐ 200 Inspection Requirements
- ☐ 300 Inspection Hold Points
- ☐ 400 Inspection Planning
- ☐ 500 In-Process Inspection
- ☐ 600 Final Inspections
- ☐ 700 Inspections During Operations
- ☐ 800 Records

☐ **11. Test Control**
- ☒ 100 Basic
- ☒ 200 Test Requirements
- ☒ 300 Test Procedures *(other than computer programs)*
- ☐ 400 Computer Program Test Procedures
- ☒ 500 Test Results
- ☒ 600 Test Records

☒ **12. Control of Measuring and Test Equipment**
- ☒ 100 Basic
- ☒ 200 Selection
- ☒ 300 Calibration and Control
- ☒ 400 Records

☐ **13. Handling, Storage and Shipping**
- ☒ 100 Basic
- ☐ 200 Special Requirements
- ☐ 300 Procedures
- ☐ 400 Tools and Equipment
- ☐ 500 Operators
- ☐ 600 Marking or Labeling

☐ **14. Inspection, Test and Operating Status**
- ☐ 100 Basic

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Appendix A: TSCR- Vent Filtration Quality Assurance Requirements

Washington River Protection Solutions
QUALITY ASSURANCE REQUIREMENTS (continued)
Revision No.: 000

Requisition No.:	Safety Classification: ☐ SC ☒ SS ☐ GS	Quality Level: ☐ QL-1 ☒ QL-2 ☐ QL-3
Quality Assurance Engineer*: John Martin	Date:	Design Authority/Engineer*: Matt Landon — Date:
Project Number: TD101	Title: TSCR Vent-Filter Testing - PNNL/LANL	

☐ **15. Control of Non-Conforming Items**
- ☒ 100 Basic
- ☐ 200 Identification
- ☐ 300 Segregation
- ☒ 400 Disposition

☐ **16. Corrective Action**
- ☒ 100 Basic

☐ **17. Quality Assurance Records**
- ☒ 100 Basic
- ☐ 200 Generation of Records
- ☐ 300 Authentication of Records
- ☐ 400 Classification
- ☐ 500 Receipt Control of Records

17. Quality Assurance Records (continued)
- ☐ 600 Storage
- ☐ 700 Retention
- ☐ 800 Maintenance of Records

☐ **18. Audits**
- ☐ 100 Basic
- ☐ 200 Scheduling
- ☐ 300 Preparation
- ☐ 400 Performance
- ☐ 500 Reporting
- ☐ 600 Response
- ☐ 700 Follow-Up Action
- ☐ 800 Records

NQA-1 Part II (Subparts) — **Quality Assurance Requirements for:**

(Specify)

Introduction *(Information Only)*
- 100 Purpose
- 200 Applicability
- 300 Responsibility
- 400 Planning and Procedures
- 500 Definitions
- 600 Multiunit Facility Provisions

2.1 Cleaning of Fluid Systems and Associated Components for Nuclear Power Plants
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Cleanness Criteria
- ☐ 400 Manufacturing Phase Cleanness
- ☐ 500 Cleanness Prior to Installation
- ☐ 600 Cleanness During Installation
- ☐ 700 Maintenance of Installation Cleanness
- ☐ 800 Preoperational Cleaning
- ☐ 900 Layup and Postlayup Cleaning
- ☐ 1000 Post-operational Repairs and Modifications
- ☐ 1100 Records

2.2 Packaging, Shipping, Receiving, Storage, and Handling of Items for Nuclear Power Plants
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Packaging
- ☐ 400 Shipping
- ☐ 500 Receiving
- ☐ 600 Storage
- ☐ 700 Handling
- ☐ 800 Records

2.3 Housekeeping for Nuclear Power Plants
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Requirements
- ☐ 400 Records

2.5 Installation, Inspection, and Testing of Structural Concrete, Structural Steel, Soils, and Foundations for Nuclear Power Plants
- 100 General *(Information Only)*
- 200 General Requirements *(Information Only)*
- ☐ 300 Requirements
- ☐ 400 Preconstruction Verification
- ☐ 500 Inspection of Soils and Earthwork
- ☐ 600 Inspection of Foundation Pile and Caisson Construction
- ☐ 700 Inspection of Concrete Construction
- ☐ 800 Inspection of Steel Construction
- ☐ 900 Data Analysis and Evaluation
- ☐ 1000 Records

2.7 Computer Software for Nuclear Facility Applications
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Software Acquisition
- ☐ 400 Software Engineering Method
- ☐ 500 Standards, Conventions, and Other Work Practices
- ☐ 600 Support Software
- 700 References *(Information Only)*

Washington River Protection Solutions
QUALITY ASSURANCE REQUIREMENTS (continued)
Revision No.: 000

Requisition No.:	Safety Classification: ☐ SC ☒ SS ☐ GS	Quality Level: ☐ QL-1 ☒ QL-2 ☐ QL-3
Quality Assurance Engineer*: John Martin	Date:	Design Authority/Engineer*: Matt Landon — Date:
Project Number: TD101	Title: TSCR Vent-Filter Testing - PNNL/LANL	

2.8 Installation, Inspection, and Testing of Mechanical Equipment and Systems for Nuclear Power Plants
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Pre-installation Verification
- ☐ 400 Control During Installation Process
- ☐ 500 Installed Systems Inspection and Tests
- ☐ 600 Data Analysis and Evaluation
- ☐ 700 Records

2.14 Commercial Grade Items and Services
- 100 General *(Information Only)*
- 200 Definition Applications *(Information Only)*
- ☐ 300 Utilization
- ☐ 400 Technical Evaluation
- ☐ 500 Critical Characteristics
- ☐ 600 Methods of Accepting Commercial Grade Items and Services
- ☐ 700 Commercial Grade Services
- ☐ 800 Documentation

2.15 Hoisting, Rigging, and Transporting of Items for Nuclear Power Plants
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Types of Handling Equipment
- ☐ 400 Design Requirements

2.15 Hoisting, Rigging, and Transporting of Items for Nuclear Power Plants (continued)
- ☐ 500 Acceptance Criteria for Manufactured Handling Equipment
- ☐ 600 Testing, Inspection, and Maintenance
- ☐ 700 Control of the Use of Handling Equipment
- ☐ 800 Qualifications of Personnel
- ☐ 900 Records

2.18 Maintenance of Nuclear Facilities
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Preventive Maintenance
- ☐ 400 Corrective Maintenance
- ☐ 500 Records

2.20 Subsurface Investigations for Nuclear Power Plants
- 100 General *(Information Only)*
- ☐ 200 General Requirements
- ☐ 300 Verification Requirements
- ☐ 400 Field Investigation Requirements
- ☐ 500 Laboratory Testing
- ☐ 600 Evaluation and Analysis
- ☐ 700 Records

Section B – Other National Standards

	National Standard Title:	ID Doc. Designation	Edition/Year	Section
a.				
b.				
c.				
d.				
e.				
f.				
g.				

Section C - Other Requirements or Clarifications, indicate requirement edition or year/date *(such as NQA-1, Part, III, or IV)*

Part 1 - Requirement 11, Test Control - The following exceptions may apply:
- Section 200, Except A "Computer Software Requirements, C, D 1-2
Part 1 - Requirement 11, Test Control
- Section 600, Except Section 602

This QAR is developed for work to be performed as Safety Related at a National Laboratory, based on work being perfomed at another DOE Site, there is not a need under the current WRPS Quality Assurance Program to evalaute and qualify Los Alamos National Laboratory for the referenced for the scope of work identified in the SOW for this work. This is based on directoin/interpretation by the current Quality Assurance Manager. Other National Labs have been qualified by DOE for the intended scope of work. This Contract will be awarded to PNNL, for work to be executed by LANL.

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Appendix B: PCB Piezotronics A2L2 Certificaiton and Scope

SCOPE OF ACCREDITATION TO ISO/IEC 17025:2017
& ANSI/NCSL Z540-1-1994 & ANSI/NCSL Z540.3-2006

PCB PIEZOTRONICS INC.
3425 Walden Avenue
Depew, NY 14043
David J. Dulanski Phone: 716 684 0002 ext 2617

CALIBRATION

Valid To: February 28, 2022 Certificate Number: 1862.01

In recognition of the successful completion of the A2LA evaluation process, accreditation is granted to this laboratory to perform the following calibrations[1, 6]:

I. Electrical – DC/Low Frequency

Parameter/Equipment	Range	CMC[2, 3, 5] (±)	Comments
DC Voltage – Measure	100 V 10 V 5 V 2 V 1 V 500 mV 200 mV 100 mV	0.082 % rdg 0.064 % rdg 0.066 % rdg 0.065 % rdg 0.067 % rdg 0.073 % rdg 0.081 % rdg 0.099 % rdg	Data acquisition card and voltage divider
DC Current – Measure	(0.5 to 100) mA	1.3 % rdg	Data acquisition card and standard resistor
AC Voltage – Measure	± 10 V ± 5 V ± 2 V ± 1 V ± 500 mV ± 200 mV ± 100 mV	0.064 % rdg 0.065 % rdg 0.065 % rdg 0.068 % rdg 0.071 % rdg 0.081 % rdg 0.087 % rdg	Data acquisition card

5202 Presidents Court, Suite 220 | Frederick, MD 21703-8515 | Phone: 301 644 3248 | Fax: 240 454 9449 | www.A2LA.org

II. Mechanical

Parameter/Equipment	Range	CMC[2, 5] (±)	Comments
Acoustic Pressure – Measure	114.0 dB SPL @ 250 Hz	0.2 dB reading (rdg)	Acoustic calibrator and pre-amplifiers
Dynamic Force (Compression/Tension) – Measure	(0 to 100 000) lbf	1 % full scale (fs)	Reference load cell
Impulse Force – Sensitivity (Voltage/Force) Measure	(0 to 5000) lbf (0 to 1000) Hz	3.8 % rdg	Quartz reference accelerometer
Static Pressure – Measure	(0 to 30) psia (0 to 60) psia (0 to 15) psig (0 to 50) psig (0 to 100) psia or psig (0 to 300) psia or psig (0 to 600) psia or psig (0 to 1000) psia or psig (0 to 3000) psia or psig (0 to 6000) psia or psig (0 to 10 000) psia or psig	0.015 % fs 0.015 % fs 0.015 % fs 0.015 % fs 0.015 % fs 0.015 % fs 0.015 % fs 0.015 % fs 0.021 % fs 0.021 % fs 0.021 % fs	DHI pressure controller/calibrator
Static Medium Pressure – Measure	(0 to 15 000) psi	1 % fs	Dead weight reference (hydraulic)
Static High Pressure – Measure	(0 to 100 000) psi	1.7 % fs	Reference pressure transducer
Dynamic Low Pressure – Measure	(0 to 100) psi 124.0 dB @ 250 Hz	1 % fs 0.45 dB rdg	Digital Heise reference pressure meter (pneumatic) Piston phone reference

Parameter/Equipment	Range	CMC[2, 4, 5] (±)	Comments
Dynamic Medium Pressure – Measure	(0 to 1000) psi	1.3 % fs	Digital Heise reference pressure meter (pneumatic)
Dynamic High Pressure – Measure	(0 to 15 000) psi	3.0 % fs	Reference pressure sensor (hydraulic)
Vibration General Purpose – Sensitivity Magnitude			
Accelerometers	(5 to 9) Hz (10 to 99) Hz (100 to 1999) Hz (2000 to 10 000) Hz (10 001 to 15 000) Hz (15 001 to 20 000) Hz	2 % rdg 1.5 % rdg 1 % rdg 2.5 % rdg 5 % rdg 9 % rdg	Reference accelerometer, back to back comparison method
Low Frequency – Sensors	(0.5 to 0.99) Hz (1 to 30) Hz (30.01 to 199) Hz (200 to 1000) Hz	1.8 % rdg 1 % rdg 1.5 % rdg 3 % rdg	Reference accelerometer with long stroke shaker, back to back comparison method
Vibration General Purpose – Acceleration Level			
Portable Shakers	(79.6 to 159.2) Hz	1.5 % rdg	Accelerometer, back to back comparison method

Parameter/Equipment	Range	CMC[2, 5] (±)	Comments
Vibration General Purpose – Sensitivity Phase			
Accelerometers	(≥5 to <10) Hz ≥10 Hz to <5 kHz (≥5 to <11) kHz (≥11 to <16) kHz (≥16 to ≤20) kHz	1° 0.75° 1.5° 2° 3°	Reference accelerometer, back to back comparison method
Low Frequency – Sensors	(≥0.5 to <10) Hz (≥10 to <200) Hz ≥200 Hz to ≤1 kHz	2.5° 0.75° 1.5°	Reference accelerometer with long stroke shaker, back to back comparison method
Primary Vibration – Sensitivity Magnitude - Measure			
Mid to High Frequency	5 Hz 5 Hz < f < 100 Hz 100 Hz< f ≤ 160 Hz 160 Hz < f ≤ 1000 Hz 1000 Hz < f ≤ 5000 Hz 5000 Hz < f ≤ 15 kHz 15 kHz < f ≤ 20 kHz	1 % rdg 0.5 % rdg 0.2 % rdg 0.5 % rdg 1 % rdg 1.5 % rdg 2.0 % rdg	Laser interferometry and shaker
Low Frequency	0.5 Hz ≤ f < 10 Hz	0.3 % rdg	Laser interferometry and long stroke shaker
Primary Vibration – Sensitivity Phase - Measure			
Mid to High Frequency	5 Hz ≤ f < 5000 Hz 5000 Hz < f ≤ 20 kHz	0.5° 1°	Laser interferometry and shaker
Low Frequency	0.5 Hz ≤ f < 10 Hz	0.5°	Laser interferometry and long stroke shaker
Acceleration Amplitude Linearity, Shock – Measure	(100 to 2000) g; (0.5 to 2) ms (>2000 to 10 000) g: (0.1 to 0.5) ms	1.9 % rdg 2.6 % rdg	Reference accelerometer with pneumatic shock tower, back to back comparison method

[1] This laboratory offers commercial calibration service.

[2] Calibration and Measurement Capability uncertainty (CMC) is the smallest uncertainty of measurement that a laboratory can achieve within its scope of accreditation when performing more or less routine calibrations of nearly ideal measurement standards or nearly ideal measuring equipment. CMCs represent expanded uncertainties expressed at approximately the 95 % level of confidence, usually using a coverage factor of $k = 2$. The actual measurement uncertainty of a specific calibration performed by the laboratory may be greater than the CMC due to the behavior of the customer's device and to influences from the circumstances of the specific calibration.

[3] CMCs are expressed as either a specific value that covers the full range or as a fraction of the reading plus a fixed floor specification.

[4] CMCs for Vibration parameters are for Sensitivity (accelerometers/sensors) or Acceleration level (shakers).

[5] The type of instrument or material being calibrated is defined by the parameter. This indicates the laboratory is capable of calibrating instruments that measure or generate the values in the ranges indicated for the listed measurement parameter.

[6] This scope meets A2LA's *P112 Flexible Scope Policy*.

Accredited Laboratory

A2LA has accredited

PCB PIEZOTRONICS INC

Depew, NY

for technical competence in the field of

Calibration

This laboratory is accredited in accordance with the recognized International Standard ISO/IEC 17025:2017 *General requirements for the competence of testing and calibration laboratories*. This laboratory also meets the requirements of ANSI/NCSL Z540-1-1994 and the requirements of ANSI/NCSL Z540.3-2006 and R205 – Specific Requirements: Calibration Laboratory Accreditation Program. This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (*refer to joint ISO-ILAC-IAF Communiqué dated April 2017*).

Presented this 26th day of February 2020.

Vice President, Accreditation Services
For the Accreditation Council
Certificate Number 1862.01
Valid to February 28, 2022

For the calibrations to which this accreditation applies, please refer to the laboratory's Calibration Scope of Accreditation.

Appendix C: Oscilloscope Manufacturer Certificate

Tektronix Inc
13725 SW Karl Braun Dr. Bldg 19
Mail Stop 19-BMC
Beaverton, OR 97077
United States

Fax:503-627-6260

CERTIFICATE OF TRACEABLE CALIBRATION

Certificate No: 2016858-2-MSO58LP-B010925-1

Contract/PO No: CC-eva v baca Warranty

Customer:

Los Alamos National Security LLC
TA-16 Bldg 328 DP01S
Bikini Atoll Rd SM30
Los Alamos, NM 87545

Model:	MSO58LP
Serial No.:	B010925
Manufacturer:	Tektronix,Inc
Description:	Low Profile Mixed Signal Oscilloscope, 1 GHz bandwidth, (8) FlexChannels with 125M record length, 3-year warranty, Certificate of Traceable Calibration Standard
Site of Calibration:	Service Center
Cal Date:	16-Jul-2020
Temperature:	24.5°C
Humidity:	56%

"Tektronix certifies the performance of the above instrument has been verified using test equipment of known accuracy, which are traceable to a National Standards Laboratory (NIST, NPL, PTB). The policies and procedures used comply with ISO/IEC 17025:2005. Reported uncertainties represent expanded uncertainties expressed at approximately the 95% confidence level using a coverage of k=2. Information about the condition of this unit (In Tolerance, Out of Tolerance) is considered an opinion and is provided for the convenience of the user.

This certificate and associated attachments relates only to the metrological quantities presented in this report. No representation is made about the long-term stability of this unit. Any number of factors can influence the calibration that may cause the unit to drift out of specification before the calibration interval has expired. This certificate shall not be reproduced, except in full, without the written approval of the calibration facility."

Appendix D: Oscilloscope LANL Calibration Certificate # 141020

Los Alamos NATIONAL LABORATORY EST 1943

Calibration Certificate

Standards & Calibration Laboratory

Certificate Number 141020

Vendor Calibration

Mail Stop: D478

File Number 117349

Contact: 338029
M-6 VIKRAM AHLUWALIA

Instrument Information:

Description:	MSO LOW PROFILE SCOPE	**File Number:**	117349
Manufacturer:	TEKTRONIX	**Property No:**	2020582
Model Number:	MSO58LP	**Other ID:**	
Serial Number:	B010925	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards.
It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	August 4, 2020		
Calibration Date:	July 16, 2020		
Certified:	Aug 28, 2020	**As Found Condition:**	INDETERMINATE
Expires:	July 16, 2021	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Initial calibration at vendor had operational failure with front panel during As Found. Item was repaired and As Left is In Tolerance.

For tolerance testing, a Test Uncertainty Ratio of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits.

Calibration Performed By:
TEKTRONIX-BEAVERTON OR — 7/16/2020
Vendor — Date

Certified By:
SKYLOR HOWARD — METROLOGIST
Name — Title

Reviewed By:
CHRISTINA MARTINEZ — 9/1/2020 2:47:58 PM
Name — Issue Date

Measurements and associated uncertainties supplied by the Standards and Calibration Laboratory (S&CL) are traceable to the International System of Units through an unbroken chain of calibrations linking individual measurements to international, national, or intrinsic standards of measurement. Each calibration in this chain is performed by a qualified calibration source meeting DOE/NNSA requirements, which generally specify adherence to ISO 17025 "General Requirements for the Competence of Testing and Calibration Laboratories". Where traceability to international, national, or instrinsic standards is not available, traceability is achieved in accordance with the requirements of ISO 17025.

This certificate of calibration must not be used by the customer to claim product endorsement by NIST, NVLAP, or any agency of the U.S. government.

End of Document

Appendix E: Pressure Sensor LW46628 LANL Certificate # 164362

Calibration Certificate

Standards & Calibration Laboratory

Vendor Calibration

Mail Stop: D478

File Number 119293

Contact: 183892
M-6 BLAKE NOLEN

Instrument Information:

Description:	PRESSURE SENSOR	**File Number:**	119293
Manufacturer:	PCB PIEZOTRONICS	**Property No:**	
Model Number:	113B22	**Other ID:**	
Serial Number:	LW46628	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards. It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	May 26, 2021		
Calibration Date:	December 30, 2020		
Certified:	May 27, 2021	**As Found Condition:**	INITIAL
Expires:	December 30, 2021	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Please see the attached calibration report for the full calibration results.

Manufacturer's Specifications: Sensitivity (1 mV/psi ± 10%), Non-Linearity (< 1.0% FS), and output bias (8 to 14 VDC).

As Found: This is an initial calibration.

As Left: This item meets manufacturer specifications.

The following are important metrics resulting from this calibration:

From 100 - 500 psi
Sensitivity: 1.013 mV/psi
Linearity: 0.1% FS
Output Bias: 10.9 VDC

From 1000 - 5000 psi
Sensitivity: 1.011 mV/psi
Linearity: 0.1% FS
Output Bias: 10.9 VDC

For tolerance testing, a Test Uncertainty Ratio (TUR) of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits specified.

Certificate Number: 164362 **Page 1 of 2**

Calibration Performed By:

PCB PIEZOTRONICS	12/30/2020
Vendor	Date

Certified By:		**Reviewed By:**	
JAMES HORNE	METROLOGIST	ROBERT BAER	5/28/2021 9:09:51 AM
Name	Title	Name	Issue Date

Measurements and associated uncertainties supplied by the Standards and Calibration Laboratory (S&CL) are traceable to the International System of Units through an unbroken chain of calibrations linking individual measurements to international, national, or intrinsic standards of measurement. Each calibration in this chain is performed by a qualified calibration source meeting DOE/NNSA requirements, which generally specify adherence to ISO 17025 "General Requirements for the Competence of Testing and Calibration Laboratories". Where traceability to international, national, or instrinsic standards is not available, traceability is achieved in accordance with the requirements of ISO 17025.

This certificate of calibration must not be used by the customer to claim product endorsement by NIST, NVLAP, or any agency of the U.S. government.

End of Document

Appendix F: Pressure Sensor LW49205 LANL Certificate # 164364

Calibration Certificate

Standards & Calibration Laboratory

Vendor Calibration

Mail Stop: D478

File Number 119294

Contact: 183892
M-6 BLAKE NOLEN

Instrument Information:

Description:	PRESSURE SENSOR	**File Number:**	119294
Manufacturer:	PCB PIEZOTRONICS	**Property No:**	
Model Number:	113B22	**Other ID:**	
Serial Number:	LW49205	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards. It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	May 26, 2021		
Calibration Date:	January 8, 2021		
Certified:	May 27, 2021	**As Found Condition:**	INITIAL
Expires:	January 8, 2022	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Please see the attached calibration report for the full calibration results.

Manufacturer's Specifications: Sensitivity (1 mV/psi ± 10%), Non-Linearity (< 1.0% FS), and output bias (8 to 14 VDC).

As Found: This is an initial calibration.

As Left: This item meets manufacturer specifications.

The following are important metrics resulting from this calibration:

From 100 - 500 psi
Sensitivity: 1.011 mV/psi
Linearity: 1.0% FS
Output Bias: 11.2 VDC

From 1000 - 5000 psi
Sensitivity: 1.009 mV/psi
Linearity: 0.3% FS
Output Bias: 11.2 VDC

For tolerance testing, a Test Uncertainty Ratio (TUR) of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits specified.

Certificate Number: 164364 **Page 1 of 2**

Appendix G: Pressure Sensor LW47057 LANL Certificate # 164367

Calibration Certificate

Standards & Calibration Laboratory

Vendor Calibration

Mail Stop: D478

File Number 119296

Contact: **183892**
M-6 **BLAKE NOLEN**

Instrument Information:

Description:	PRESSURE SENSOR	**File Number:**	119296
Manufacturer:	PCB PIEZOTRONICS	**Property No:**	
Model Number:	113B22	**Other ID:**	
Serial Number:	LW47057	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards. It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	May 26, 2021		
Calibration Date:	December 29, 2020		
Certified:	May 27, 2021	**As Found Condition:**	INITIAL
Expires:	December 29, 2021	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Please see the attached calibration report for the full calibration results.

Manufacturer's Specifications: Sensitivity (1 mV/psi ± 10%), Non-Linearity (< 1.0% FS), and output bias (8 to 14 VDC).

As Found: This is an initial calibration.

As Left: This item meets manufacturer specifications.

The following are important metrics resulting from this calibration:

From 100 - 500 psi
Sensitivity: 0.9968 mV/psi
Linearity: 0.2% FS
Output Bias: 11.05 VDC

From 1000 - 5000 psi
Sensitivity: 0.9982 mV/psi
Linearity: 0.09% FS
Output Bias: 11.05 VDC

For tolerance testing, a Test Uncertainty Ratio (TUR) of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits specified.

Certificate Number: 164367 **Page 1 of 2**

Calibration Performed By:

PCB PIEZOTRONICS			12/29/2020
Vendor			Date

Certified By:		**Reviewed By:**	
JAMES HORNE	METROLOGIST	ROBERT BAER	5/28/2021 9:13:54 AM
Name	Title	Name	Issue Date

Measurements and associated uncertainties supplied by the Standards and Calibration Laboratory (S&CL) are traceable to the International System of Units through an unbroken chain of calibrations linking individual measurements to international, national, or intrinsic standards of measurement. Each calibration in this chain is performed by a qualified calibration source meeting DOE/NNSA requirements, which generally specify adherence to ISO 17025 "General Requirements for the Competence of Testing and Calibration Laboratories". Where traceability to international, national, or instrinsic standards is not available, traceability is achieved in accordance with the requirements of ISO 17025.

This certificate of calibration must not be used by the customer to claim product endorsement by NIST, NVLAP, or any agency of the U.S. government.

End of Document

Appendix H: Pressure Sensor LW47056 LANL Certificate # 164366

Calibration Certificate

Standards & Calibration Laboratory

Vendor Calibration

Mail Stop: D478

File Number 119295

Contact: 183892
M-6 BLAKE NOLEN

Instrument Information:

Description:	PRESSURE SENSOR	**File Number:**	119295
Manufacturer:	PCB PIEZOTRONICS	**Property No:**	
Model Number:	113B22	**Other ID:**	
Serial Number:	LW47056	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards. It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	May 26, 2021		
Calibration Date:	December 30, 2020		
Certified:	May 27, 2021	**As Found Condition:**	INITIAL
Expires:	December 30, 2021	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Please see the attached calibration report for the full calibration results.

Manufacturer's Specifications: Sensitivity (1 mV/psi ± 10%), Non-Linearity (< 1.0% FS), and output bias (8 to 14 VDC).

As Found: This is an initial calibration.

As Left: This item meets manufacturer specifications.

The following are important metrics resulting from this calibration:

From 100 - 500 psi
Sensitivity: 1.004 mV/psi
Linearity: 0.10% FS
Output Bias: 11.95 VDC

From 1000 - 5000 psi
Sensitivity: 1.003 mV/psi
Linearity: 0.10% FS
Output Bias: 11.95 VDC

For tolerance testing, a Test Uncertainty Ratio (TUR) of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits specified.

Certificate Number: 164366 **Page 1 of 2**

Calibration Performed By:

PCB PIEZOTRONICS			12/30/2020
Vendor			Date

Certified By:		**Reviewed By:**	
JAMES HORNE	METROLOGIST	ROBERT BAER	5/28/2021 9:12:41 AM
Name	Title	Name	Issue Date

Measurements and associated uncertainties supplied by the Standards and Calibration Laboratory (S&CL) are traceable to the International System of Units through an unbroken chain of calibrations linking individual measurements to international, national, or intrinsic standards of measurement. Each calibration in this chain is performed by a qualified calibration source meeting DOE/NNSA requirements, which generally specify adherence to ISO 17025 "General Requirements for the Competence of Testing and Calibration Laboratories". Where traceability to international, national, or instrinsic standards is not available, traceability is achieved in accordance with the requirements of ISO 17025.

This certificate of calibration must not be used by the customer to claim product endorsement by NIST, NVLAP, or any agency of the U.S. government.

End of Document

Appendix I: Pressure Sensor 15343 LANL Certificate # 164369

Calibration Certificate

Standards & Calibration Laboratory

Vendor Calibration

Mail Stop: D478

File Number 119292

Contact: **183892**
M-6 **BLAKE NOLEN**

Instrument Information:

Description:	PRESSURE SENSOR	**File Number:**	119292
Manufacturer:	PCB PIEZOTRONICS	**Property No:**	
Model Number:	137B23A	**Other ID:**	
Serial Number:	15343	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards.
It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	May 26, 2021		
Calibration Date:	January 20, 2021		
Certified:	May 27, 2021	**As Found Condition:**	INITIAL
Expires:	January 20, 2022	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Please see the attached calibration report for the full calibration results.

Manufacturer's Specifications: Sensitivity (100 mV/psi ± 15%), Non-Linearity (< 1.0% FS), and output bias (8 to 15 VDC).

As Found: This is an initial calibration.

As Left: This item meets manufacturer specifications.

The following are important metrics resulting from this calibration:
Sensitivity: 100.2 mV/psi
Linearity: 0.1% FS
Output Bias: 12.5 VDC

For tolerance testing, a Test Uncertainty Ratio (TUR) of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits specified.

Certificate Number: 164369 **Page 1 of 2**

Calibration Performed By:

PCB PIEZOTRONICS	1/20/2021
Vendor	Date

Certified By:		**Reviewed By:**	
JAMES HORNE	METROLOGIST	ROBERT BAER	5/28/2021 7:44:30 AM
Name	Title	Name	Issue Date

Measurements and associated uncertainties supplied by the Standards and Calibration Laboratory (S&CL) are traceable to the International System of Units through an unbroken chain of calibrations linking individual measurements to international, national, or intrinsic standards of measurement. Each calibration in this chain is performed by a qualified calibration source meeting DOE/NNSA requirements, which generally specify adherence to ISO 17025 "General Requirements for the Competence of Testing and Calibration Laboratories". Where traceability to international, national, or instrinsic standards is not available, traceability is achieved in accordance with the requirements of ISO 17025.

This certificate of calibration must not be used by the customer to claim product endorsement by NIST, NVLAP, or any agency of the U.S. government.

End of Document

Appendix J: Pressure Sensor 15342 LANL Certificate # 164368

Calibration Certificate

Standards & Calibration Laboratory

Vendor Calibration

Mail Stop: D478

File Number 119291

Contact: **183892**
M-6 **BLAKE NOLEN**

Instrument Information:

Description:	PRESSURE SENSOR	**File Number:**	119291
Manufacturer:	PCB PIEZOTRONICS	**Property No:**	
Model Number:	137B23A	**Other ID:**	
Serial Number:	15342	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards.
It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	May 26, 2021		
Calibration Date:	January 20, 2021		
Certified:	May 27, 2021	**As Found Condition:**	INITIAL
Expires:	January 20, 2022	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Please see the attached calibration report for the full calibration results.

Manufacturer's Specifications: Sensitivity (100 mV/psi ± 15%), Non-Linearity (< 1.0% FS), and output bias (8 to 15 VDC).

As Found: This is an initial calibration.

As Left: This item meets manufacturer specifications.

The following are important metrics resulting from this calibration:
Sensitivity: 103.8 mV/psi
Linearity: 0.2% FS
Output Bias: 12.6 VDC

For tolerance testing, a Test Uncertainty Ratio (TUR) of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits specified.

Certificate Number: 164368 **Page 1 of 2**

Calibration Performed By:

PCB PIEZOTRONICS	1/20/2021
Vendor	Date

Certified By:		**Reviewed By:**	
JAMES HORNE	METROLOGIST	ROBERT BAER	5/28/2021 7:42:45 AM
Name	Title	Name	Issue Date

Measurements and associated uncertainties supplied by the Standards and Calibration Laboratory (S&CL) are traceable to the International System of Units through an unbroken chain of calibrations linking individual measurements to international, national, or intrinsic standards of measurement. Each calibration in this chain is performed by a qualified calibration source meeting DOE/NNSA requirements, which generally specify adherence to ISO 17025 "General Requirements for the Competence of Testing and Calibration Laboratories". Where traceability to international, national, or instrinsic standards is not available, traceability is achieved in accordance with the requirements of ISO 17025.

This certificate of calibration must not be used by the customer to claim product endorsement by NIST, NVLAP, or any agency of the U.S. government.

End of Document

Appendix K: Signal Conditioner 555 LANL Certificate # 164386

Calibration Certificate

Standards & Calibration Laboratory

Vendor Calibration

Mail Stop: D478

File Number 119290

Contact: **183892**
M-6 **BLAKE NOLEN**

Instrument Information:

Description:	SIGNAL CONDITIONER	**File Number:**	119290
Manufacturer:	PCB PIEZOTRONICS	**Property No:**	
Model Number:	483C15	**Other ID:**	
Serial Number:	555	**Customer Required ID:**	

Calibration Information:

Calibration of the above item was achieved in a controlled environment through the use of equipment traceable to national standards. It is expected that for the duration of the calibration interval and under normal operational conditions, this item will remain within the tolerance limits specified. Unless otherwise stated, expressed measurement uncertainty represents a confidence level of approximately 95%, typically with a coverage factor of k=2.

Received Date:	May 26, 2021		
Calibration Date:	December 22, 2020		
Certificd:	May 27, 2021	**As Found Condition:**	INITIAL
Expires:	December 22, 2021	**As Left Condition:**	IN TOLERANCE
Interval:	365 DAYS	**Result:**	PASS

Results:

Please see the attached calibration report for the full calibration results.

Manufacturer Specifications: Voltage Gain x1,x10,x100 (± 1%).

As Found: This is an initial calibration.

As Left: This item meets manufacturer specifications.

For tolerance testing, a Test Uncertainty Ratio (TUR) of at least 4:1 was obtained or the results were guard banded to ensure conformance to the tolerance limits specified.

Certificate Number: 164386 **Page 1 of 2**

Calibration Performed By:

PCB PIEZOTRONICS			12/22/2020
Vendor			Date

Certified By:		**Reviewed By:**	
JAMES HORNE	METROLOGIST	ROBERT BAER	5/28/2021 6:54:13 AM
Name	Title	Name	Issue Date

Measurements and associated uncertainties supplied by the Standards and Calibration Laboratory (S&CL) are traceable to the International System of Units through an unbroken chain of calibrations linking individual measurements to international, national, or intrinsic standards of measurement. Each calibration in this chain is performed by a qualified calibration source meeting DOE/NNSA requirements, which generally specify adherence to ISO 17025 "General Requirements for the Competence of Testing and Calibration Laboratories". Where traceability to international, national, or instrinsic standards is not available, traceability is achieved in accordance with the requirements of ISO 17025.

This certificate of calibration must not be used by the customer to claim product endorsement by NIST, NVLAP, or any agency of the U.S. government.

End of Document

Appendix L: Stacks Cheeta Run Report

Cheetah 8.0 Run Report

Thu Apr 02 08:48:02 MDT 2020

By 199639

```
################################################################################
#                                                                              #
#                        CHEETAH 8.0 SUMMARY SHEET                             #
#                        Energetic Materials Center                            #
#                  Lawrence Livermore National Laboratory                      #
#                          Email: cheetah@llnl.gov                             #
#          Copyright 2015, Lawrence Livermore National Security                #
#                           All Rights Reserved                                #
#                                                                              #
################################################################################


################################################################################
################################################################################


Product library title: exp6i.v8.0 $revision: 2871 $
Reactant library title: The Cheetah GUI XML file
COMPOSITION:
                                     Heat of       Molar
Name              % wt   % mol  % vol  formation     weight     TMD      Formula
                                      [cal/mol]     [g]        [g/cc]
hydrogen           4.38  50.00  52.36  0.0000e+000   2.016      0.000    h2
nitrous oxide     95.62  50.00  47.64  1.9613e+004   44.013     0.002    n2o1

Molecular formula: h 1 n 1 o 0.5
Oxygen balance (by mass)   = -0%
Heat of formation   = 4.2610e+002 cal/g

################################################################################
################################################################################

Density  =  0.0010 g/cc   Mixture TMD =  0.0010 g/cc   % TMD = 99.9948

CHAPMAN-JOUGUET CONDITION:
Pressure          =          0.003 GPa
Volume            =        551.627 cc/g
Density           =          0.002 g/cc
Energy            =          0.001 kJ/cc explosive
Temperature       =         3554.1 K
Shock velocity    =          2.387 km/s
Particle velocity =          1.090 km/s
Speed of sound    =          1.297 km/s
Gamma             =          1.107

CYLINDER DATA:             % of standards
   V/V0    Energy    TATB     PETN      HMX    CL-20      TNT
           [kJ/cc] 1.83g/cc 1.76g/cc 1.89g/cc 2.04g/cc 1.64g/cc
   1.00    -0.00       0        0        0        0        0
```

2.20	-0.00	0	0	0	0	0
4.40	-0.00	0	0	0	0	0
7.20	-0.00	0	0	0	0	0
10.00	-0.00	0	0	0	0	0
20.00	-0.00	0	0	0	0	0
50.00	-0.00	0	0	0	0	0
100.00	-0.00	0	0	0	0	0
200.00	-0.01	0	0	0	0	0

Chemistry "freeze" occurs at T = 2300.0 K and relative V = 30.582
Freeze command: freeze, *c-diamond, *c-graphite, co2, co

PERFORMANCE:

	Units	This explosive	TNT	TNT equivalence
Total energy	kJ/cc	-6.9363e-003	-7.3805e+000	0.001 (per cc)
of detonation	kJ/g	-7.0419e+000	-4.4622e+000	1.578 (per gram)
Mechanical energy	kJ/cc	-2.8108e-003	-7.1889e+000	0.000 (per cc)
of detonation	kJ/g	-2.8536e+000	-4.3464e+000	0.657 (per gram)
Thermal energy	kJ/cc	-4.1255e-003	< 0.1	N/A
of detonation	kJ/g	-4.1884e+000	< 0.1	N/A
Heat	cal/g	1.6859e+003	3.4725e+003	0.486 (per gram)
of combustion	kJ/g	7.0539e+000	1.4529e+001	0.486 (per gram)

JWL FIT RESULTS:
E0 = -0.0028 kJ/cc
A = 0.0454 GPa, B = 0.0028 GPa , C = -0.0000 GPa
R[1] = 8.0000, R[2] = 0.5000, omega = 0.0500
RMS fitting error = 23.948 %